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Overview of Scientific Progress. "Head-related transfer functions" (HRTFs) capture the direction-dependent filter characteristics of the external ears. When a sound is filtered by HRTFs measured from a listener's own ears and played over headphones, the listener hears a virtual source that is well localized in space. When sounds were filtered by other listeners' HRTFs, listeners showed fairly accurate localization in the lateral dimension but showed conspicuous vertical and front/back errors. We examined differences among HRTFs measured from 45 listeners. We quantified differences by subtracting HRTFs between listeners for corresponding locations, then computing the variance of the resulting difference spectra across 393 locations. Inter-listener differences could be reduced by shifting HRTFs scaling in frequency. Optimal scalars reduced variances by an average of 20.2% across all pairs of listeners and by more than 50% in 9.5% of listener pairs. The optimal scalar for any pair of listeners correlated highly with the relative sizes of certain physical dimensions. When HRTFs were shifted optimally then used in virtual localization trials, all measures of virtual localization performance tended to improve. In the majority of cases, the performance penalty for use of HRTFs from another listener was reduced by more than half.

Description of Scientific Accomplishments. The principal objective of this research project was to develop techniques by which head-related transfer functions (HRTFs) can be processed for inter-listener differences, thus making virtual auditory environment technology accessible to a broad range of listeners. The major classes of results are that individual differences can be reduced by more than half by scaling HRTFs in frequency and that frequency scaling of HRTFs result in substantial improvements in location of virtual targets under conditions in which listeners use HRTFs recorded from other listeners. Specific accomplishments are described below:

- We recorded HRTFs from 45 human listeners. Each set of HRTFs consisted of recordings from left and right ears for sound sources at 400 locations in azimuth and elevation. For the purpose of quantitative evaluation, each HRTF was processed with a bank of 85 narrowband filters, and a spatial interpolation procedure was used to obtain processed HRTFs at 393 locations, each representing a constant solid angle.
- We devised a metric to represent the differences between sets of HRTFs for each pair of listeners. Log magnitudes in dB of HRTFs for each source location were subtracted, one subject from the other, across a frequency band from 3.7 to 12.9 kHz, then the variances of the resulting difference spectra were computed. Inter-listener variances for each pair of subjects were averaged across all 393 locations.
- Visual inspection of HRTFs indicated that HRTFs from various listeners appeared to vary systematically in the position of spectral features (i.e., peaks and notches) along the frequency axis. We found that inter-listener variances could be reduced by scaling HRTFs in frequency (or, equivalently, shifting in octave frequency). Scaling by optimal values reduced variances by an average of 20.2% across all 990 pair-wise combinations of 45 listeners and by more than half in 9.5% of listener pairs. The mean magnitude of the optimal octave frequency shift across all pairs of subjects was 0.107 octave (i.e., a scalar of 107.7%).

- Optimal scalars between pairs of listeners correlated with a measure of the ratios of their maximum interaural time differences ( $r = .68$ ).
- Optimal scalars correlated with certain physical dimensions. We measured the widths of listeners' heads and several dimensions of their external ears. The highest correlation was a correlation of  $r = .82$  between octave frequency scalars and a weighted sum of the width of the head and the height of the pinna (from inter-tragal notch to the helix).
- We tested the accuracy of localization of virtual targets under conditions in which listeners used HRTFs recorded from their own ears (the *own-ear* condition), in which HRTFs were recorded from other listeners (the *other-ear* condition), and in which HRTFs from other listeners were scaled optimally in frequency (the *scaled-ear* condition). Fourteen subjects were tested in the own-ear condition and in a total of 58 cases in the other-ear condition. Eleven of the listeners also were tested in the scaled-ear condition in a total of 21 cases.
- In the other-ear condition, listeners localized fairly accurately in the lateral dimension, although the smallest listeners (i.e., those with short interaural delays) tended to overshoot the targets when listening through HRTFs measured from larger listeners. Similarly, large listeners tended to undershoot when listening through HRTFs measured from small listeners.
- Listeners tended to show conspicuous localization errors in the vertical and front/back dimensions. These errors included systematic errors in the vertical dimension within a particular quadrant and "quadrant errors" in which targets were mislocalized to the wrong down-front, up-front, up-rear, or down-rear quadrant.
- In cases in which small listeners used HRTFs from larger listeners: 1) down-front targets often were localized to up-front; 2) up-rear targets often were localized to up-front; and 3) front/back confusions were more common than up/down confusions.
- In cases in which large listeners used HRTFs from smaller listeners: 1) there was a substantial rate of front/back confusions, although the rate was lower than in small-listener/large-HRTF cases; and 2) in trials in which there was no quadrant error, there was a systematic upward bias in location judgements.
- The magnitude of virtual-localization errors and the rate of quadrant errors increased in proportion to the inter-listener variance between a listener's own HRTFs and the HRTFs through which he or she listened.
- Nearly every quantitative measure of localization accuracy improved when the inter-listener variance between HRTFs was reduced by scaling in frequency. In 62% of cases, the increase in vertical and front/back error in the other-ear compared to the own-ear condition was reduced by more than half by scaling in frequency.

Papers submitted to refereed journals:

Middlebrooks, J.C. (1998) Individual differences in external-ear transfer functions reduced by scaling in frequency. Submitted to J. Acoust. Soc. Am. (in revision).

Middlebrooks, J.C. (1998) Virtual localization improved by scaling non-individualized external-ear transfer functions. Submitted to J. Acoust. Soc. Am. (in revision).

Published book chapters:

Middlebrooks JC: Spectral shape cues for sound localization. In: Binaural and Spatial Hearing in Real and Virtual Environments, (Gilkey and Anderson, eds.), Lawrence Erlbaum Associates, Inc., Mahwah, N.J., pp. 77-97, 1997.

Abstracts published and in press:

Xu, L, Furukawa, S, and Middlebrooks, JC: Responses of auditory cortical neurons to sounds that produce spatial illusions. Neurosci Abst. 24:1402, 1998.

Middlebrooks, JC: Sound localization using other people's ears. J. Acoust. Soc. Am. (to be presented at Berlin ASA meeting, March, 1999)